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An Analytic Description of a Harmonic Decomposition Technique for Correcting Signal Errors Due to Wideband Radar Phase Detector

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Abstract

A signal processing technique is presented for correcting imbalances and distortions introduced to the signals by the phase detectors of a coherent wideband radar. The signal model and sources of signal errors are described, an analytic description of how the corrections are derived is provided, and a sample application is presented with the use of simulated data. This report has been prepared in anticipation of a subsequent report in which the performance of this signal processing technique will be compared with the performances of several other techniques developed for similar purposes with actual data measured in the field.

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1. Introduction

The U.S. Army Research Laboratory (ARL) has a variety of instrumentation radars for research related to sensor technologies, to include modeling, simulation, analysis, and signal processing of radar signatures. Before any of these research objectives are met, the data collected by the instrumentation radars must be calibrated to relate the returned signal to the transmitted signal. This calibration removes errors introduced by components of the radar and scales the data. In particular, ARL's Millimeter-Wave Branch of the Radio Frequency (rf) and Electronics Division has several inverse synthetic aperture radars containing phase detectors that require error correction. As these new radars are developed and introduced, new calibration techniques have been developed so that three distinct techniques are now being used. Two of these techniques, the method of Wallace and Pizzillo[1] and a phase modulation and demodulation technique,[2] have been documented as ARL technical reports. The third, a harmonic decomposition technique, has only been documented as an algorithm in software.

This report provides an analytic description of the third algorithm in anticipation of publishing a report detailing a comparison of the three techniques with the use of data collected by the state-of-the-art 35-GHz monopulse instrumentation radar. This instrument uses the phase modulation and demodulation technique, an architecture-based calibration, and the only one of the various radars that can collect data that may be corrected by all three techniques, thereby allowing a direct comparison of the efficiency and accuracy of each scheme.

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[1]H. Bruce Wallace and Thomas J. Pizzillo, *A Technique for Calibrating the Phase Detector of a Wideband Radar Using an External Target*, U.S. Army Research Laboratory, ARL-TR-1521 (March 1998).

[2]Thomas J. Pizzillo and H. Bruce Wallace, *A Technique for Calibrating the Phase Detector of Wideband Radars Using a Phase Modulation and Demodulation Scheme*, U.S. Army Research Laboratory, ARL-TR-1567 (May 1998).

2. Derivation of Correction Terms

Figure 1 is a simplified block diagram of a polarimetric, two-coordinate, amplitude-comparison monopulse system operating at 94 GHz, with a 640-MHz bandwidth. Either linearly or circularly polarized radiation is transmitted and both components are received, i.e., left-circular transmit and right- and left-circular receive or vertical transmit and vertical and horizontal receive. Transmit polarization may be changed to pulse to pulse or ramp to ramp.

The rf local oscillator (LO) is frequency-stepped synchronously with the transmitter and maintains a constant 3-GHz offset. This source is mixed with the received signal to provide the 3-GHz intermediate frequency (IF) to the in-phase/quadrature (I/Q) detectors. The IF is mixed with the 3-GHz LO to provide the final direct current (DC) signal to the analog-to-digital converter (ADC). The 3-GHz LO is also the source of the injected test signal used for correcting the phase and gain imbalances introduced by the I/Q detectors. A simplified block diagram of the IF section is shown in figure 2. This test signal is

$$S = A \cos 2\pi f \ , \tag{1}$$

where f represents the test signal's constant frequency and A is the amplitude of the test signal. However, this only provides a single DC output

Figure 1. Simplified block diagram of a monopulse radar.

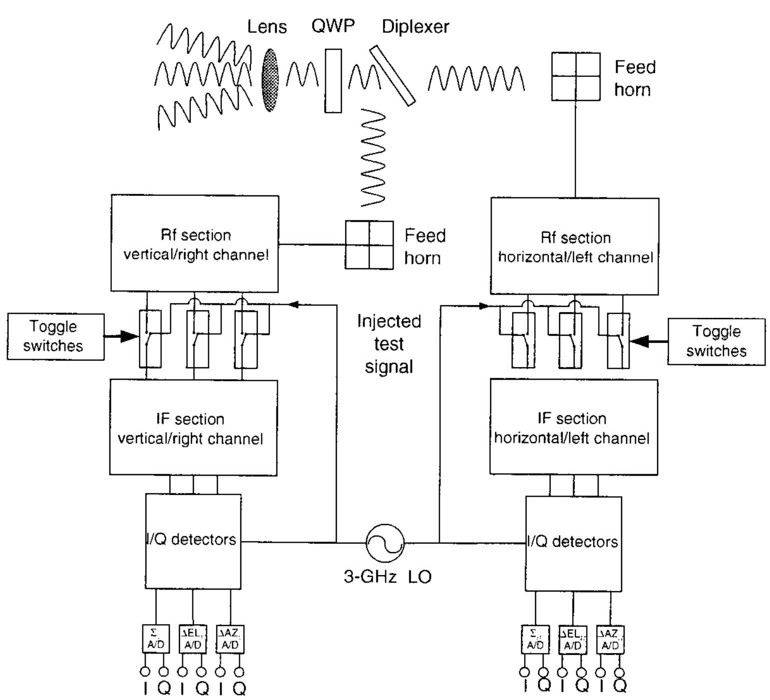
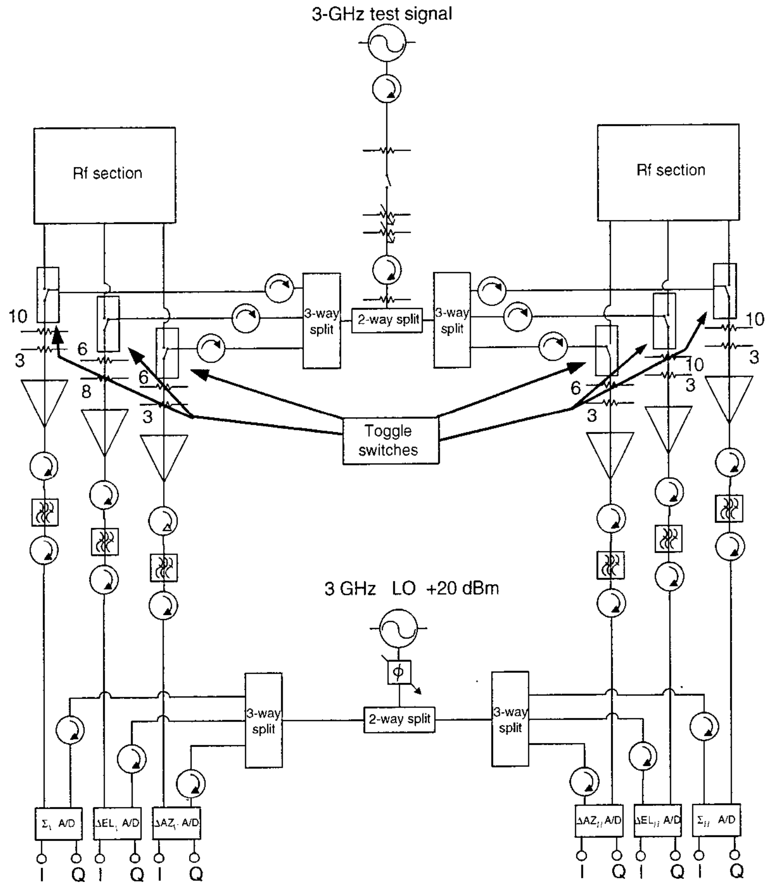


Figure 2. Simplified block diagram of IF section of a monopulse radar.



value for a given frequency from the I/Q detectors, and correcting the output of the detectors over a range of frequencies is necessary. To accomplish this, one must phase-modulate the test signal to provide an input to the I/Q detectors as

$$S(m) = A\cos\left(2\pi f + 2\pi\frac{m}{M}\right) , \tag{2}$$

where M is an even integer representing the number of phase modulation steps. Shifting the phase creates a pseudo-time-sampled signal with frequency of 1 Hz and a period of $1/M$. This signal is injected at the IF section and then propagates through the phase detector, where a second signal, shifted 90° relative to the test signal, is generated. These signals are referred to as the I and Q channels of the detector:

$$\begin{aligned} \mathbf{I}(m) &= A\cos\left(2\pi\frac{m}{M}\right) + V_i \quad \text{and} \\ \mathbf{Q}(m) &= GA\sin\left(2\pi\frac{m}{M} + \delta\right) + V_q , \end{aligned} \tag{3}$$

where V_i and V_q are DC-offsets and G and δ represent the relative gain and phase imbalances between the outputs of I and Q channels, all introduced by the imperfect detector. The $2\pi f$ term has been eliminated because the detection is a mixing process with f as the baseband. At this juncture, these errors could be corrected by the method described in Wallace and Pizzillo. However, in addition to the errors introduced by the phase detector, the components that compose the IF section cause nonlinear distortion of the signal so that the signals may be better modeled by a set of trigonometric polynomials,

$$
\begin{aligned}
\mathbf{I}(M) &= \sum_{n=0}^{N} A_n \cos\left(2n\pi\frac{m}{M}\right) + V_i \quad N = 0, 2, 4 \ldots \frac{M}{2} \\
\mathbf{Q}(M) &= \sum_{n=0}^{N} B_n \sin\left(2n\pi\frac{m}{M}\right) + V_q \quad N = 1, 3, 5, \ldots \left(\frac{M}{2} - 1\right) \; . \qquad (4)
\end{aligned}
$$

Although the phase and gain imbalance of the phase detector creates a response at the image range bin,[3] this error is subsumed by the appropriate terms and coefficients of the polynomial and needs not be explicitly enumerated. Equation (4) represents a set of functions orthogonal on the complex plane over the range $[-\pi, \pi]$. Hence, the coefficients A_n and B_n may be determined via the complex fast Fourier transform (CFFT) of the measured I/Q detector outputs by

$$
\begin{aligned}
F\left[\mathbf{I}(M), \mathbf{Q}(M)\right] &= \sum_{n=0}^{N} \left\{ A_n \cos\left(2n\pi\frac{m}{M}\right) + iB_n \sin\left(2n\pi\frac{m}{M}\right) + V \right\} \exp\left(2\pi j\frac{k}{M}\right) \\
&= \mathbf{I}(K) + i\mathbf{Q}(K) , \qquad (5)
\end{aligned}
$$

where $V = V_i + V_q$ and $\mathbf{I}(K)$ and $\mathbf{Q}(K)$ are the M outputs of the CFFT that represent the harmonic coefficients of the transformed signal. That is, for each k, only the trigonometric component $k = n$ contributes

$$
\begin{aligned}
\mathbf{I}(K) &= A_0 + A_2 \cos\left(2\pi\frac{2}{M}\right) + \ldots + A_{M-2} \cos\left(2\pi\frac{M-2}{M}\right) , \quad \text{and} \\
\mathbf{Q}(K) &= B_1 \sin\left(2\pi\frac{1}{M}\right) + B_3 \sin\left(2\pi\frac{3}{M}\right) + \ldots + B_{\frac{M-2}{2}} \sin\left(2\pi\frac{M-2}{2M}\right) . \qquad (6)
\end{aligned}
$$

The maximum number of contributing harmonics is determined by the Nyquist rate or $M/2$ distributed symmetrically about the fundamental:

$$
\begin{aligned}
\mathbf{I}(K) &= A_0 + A_{\frac{-M}{2}} \cos(-\pi) + \ldots + A_{\frac{M}{2}} \cos(\pi) , \quad \text{and} \\
\mathbf{Q}(K) &= B_{\frac{2-M}{2}} \sin\left(2\pi\frac{2-M}{2M}\right) + \ldots + B_{\frac{M-2}{2}} \sin\left(2\pi\frac{M-2}{2M}\right) . \qquad (7)
\end{aligned}
$$

By repeating this procedure for several amplitudes and storing the values in a lookup table, one may correct any measured amplitude on the complex plane defined by **I** and **Q** up to the maximum calibration amplitude.

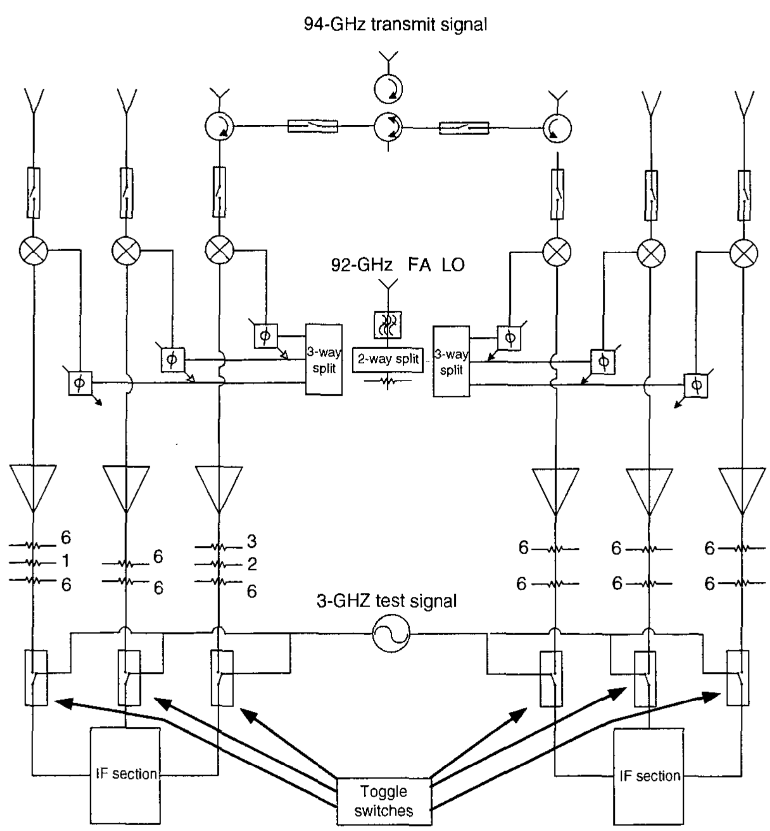
[3]Merril Skolnik, *Radar Handbook,* 2nd ed., McGraw-Hill, Inc. (1990), p 3.41.

3. Technique Application

The correction noted in section 2 is applied in the following procedure: A constant amplitude signal is injected into the IF section of the radar via the toggle switches (see fig. 2). This provides a DC signal to the ADC. Data are collected at 16 phase angles, $22.5°m$, where $m = 0,1 \ldots 15$, controlled by the phase-shifter shown in figure 3 for both the I and Q channels. Six thousand four hundred samples are averaged for each phase setting to minimize noise. The data are converted to signed integer values by subtracting half the dynamic range of the ADC from each set, i.e., 2048. A complex value is generated from the I and Q data and then sorted from the minimum to maximum phase. This process is repeated for four attenuation levels: 98, 78, 58, and 39 percent of the A/D dynamic range, i.e., 4095. The final results are four sets of complex data of 16 values each from which the correction coefficients are derived.

The correction coefficients are used to correct measured data in both phase and amplitude by subtracting the unwanted harmonic components from each measured data point, I_m and Q_m. Measured amplitudes are corrected with the correction amplitudes above and below the measured value, with

Figure 3. Simplified block diagram of rf section of a monopulse radar.



an appropriate weighting factor. This weighting factor is calculated with

$$W_u = \frac{(A_u - A_m)}{(A_u - A_l)} \quad W_l = \frac{(A_m - A_l)}{(A_u - A_l)} ; \quad (W_u + W_l = 1) \; . \tag{8}$$

where A_u is the correction amplitude greater than the measured value, A_l is the correction amplitude less than the measured value, and $A_m = \sqrt{I_m^2 + A_m^2}$ = the amplitude of the measured I and Q data points.

Consider the simulated data in figure 4 created for M = 16. The set of measured I/Q pairs is indicated with squares and falls between the calibration amplitudes, A_u = 1500 and A_l = 1200. The corrected I and Q values are determined by

$$\begin{aligned} I_c &= I_m - W_u \left[A_{0u} + A_{-8u}\cos(-8\theta_m) + \ldots + A_{8u}\cos(8\theta_m)\right] \\ &\quad - W_l \left[A_{0l} + A_{-8l}\cos(-8\theta_m) + \ldots + A_{8l}\cos(8\theta_m)\right] \; , \quad \text{and} \\ Q_c &= Q_m - W_u \left[A_{-7u}\sin(-7\theta_m) + \ldots + A_{7u}\sin(7\theta_m)\right] \\ &\quad - W_l \left[A_{-7l}\sin(-7\theta_m) + \ldots + A_{7l}\sin(7\theta_m)\right] \; , \end{aligned} \tag{9}$$

where I_c and Q_c are the corrected I and Q data points. $\theta_m = \arctan 2\left(\frac{Q_m}{I_m}\right)$ is the measured relative phase between I_m and Q_m. A_{nu} and A_{nl} are the nth harmonic coefficient for the upper and lower calibration bounds, respectively. These expressions are applied to each of the 16 I/Q pairs indicated with circles in figure 4. This example is for demonstration only and for clarifying the application of this technique. A subsequent report will compare the application of this technique to measured data, and its performance will be compared with two other techniques developed for the same data correction problem.

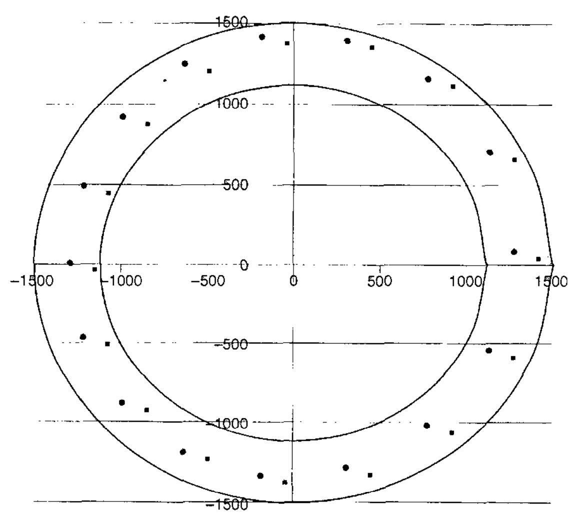


Figure 4. Simulated I/Q data: Squares indicate measured data and circles indicate corrected data.

4. Conclusion

An algorithm currently used by ARL (Millimeter-Wave Branch) for correcting the I and Q errors introduced by the phase detectors of a wideband radar has been presented. The signals with errors have been modeled as trigonometric polynomials and the correction described as a harmonic decomposition based upon the CFFT. An analysis of the performance of this technique is left for a subsequent publication in which the performance of the two other techniques (see sect. 1) will be compared along with the results of this harmonic decomposition as applied to actual measured data from a state-of-the-art 35-GHz monopulse instrumentation radar.

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